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TRACTION-DRIVE, SEVEN-DEGREE-OF-FREEDOM TELEROBOT ARM: A CONCEPT FOR MANIPULATION IN SPACE*

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ABSTRACT

As man seeks to expand his dominion into new environments, the demand increases for machines that perform useful functions in remote locations. This new concept for manipulation in space is based on knowledge and experience gained from manipulator systems developed to meet the needs of remote nuclear applications. It merges the best characteristics of teleoperation and robotic technologies. This paper summarizes the report of a study performed for NASA Langley Research Center.[1] The design goals for the telerobot, a mechanical description, and technology areas that must be addressed for successful implementation will be presented and discussed. The concept incorporates mechanical traction drives, redundant kinematics, and modular arm subelements to provide a backlash-free manipulator capable of obstacle avoidance. Further development of this arm is in progress at the Oak Ridge National Laboratory.

INTRODUCTION

The national commitment to establish a permanent operating space station signifies that man has progressed beyond exploration of space to habitation in space. As the Space Station Program develops, remote manipulation will play a critical role in the successful use of space. Remote manipulation advances will increase the domain where useful work can be performed (e.g., polar orbits pose health hazards for extravehicular activity), and automated manipulation will reduce manpower requirements for construction and routine operations in space. As manipulators are developed for space, it is envisioned that the advanced mechanical, sensory, and control technologies generated to support this action will fertilize industrial robotic applications and improve terrestrial productivity. With these useful results in mind, the information presented here was developed to address the technical aspects of designing a manipulation system that could expand with the advances in sensory and control technology that are certain to occur within the next decade.

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DESIGN GOALS

The Shuttle Remote Manipulator System (RMS) has demonstrated its usefulness in the capture, repair, and deployment of satellites. The large reach of this system makes it suitable for manipulation of sizable structures and objects in the microgravity of space. Smaller, more dexterous manipulation systems will be required to perform satellite maintenance, some aspects of space structure construction, and vehicle refueling operations. The purpose of developing a telerobotic work package for space application is to increase astronaut and system safety, productivity, and flexibility. Astronaut risks increase as the demand for extravehicular activities (EVA) time increases for large projects such as space station assembly, operation, and maintenance. A telerobotic remote handling system can accomplish many tasks in the time required for an astronaut to "breathe down" to prepare for EVA tasks. Telerobotic systems also make round-the-clock operations possible, while the operating crew remains safe within the orbiter or space station.

The focus of this effort is the development of a manipulator system capable of performing a range of manipulation tasks presently accomplished by astronauts during EVA. The manipulation capabilities of astronauts are significantly reduced as a result of the protective suit and its pressurization. In fact, the dexterity of the human hand is so diminished that an entire set of special tooling has been developed through the years for use in EVA tasks. The suited human arm, while bulky, does retain its kinematic redundancies, thereby allowing the arm to avoid obstacles and approach the worksite in a number of ways. The suited astronaut does have sensory and judgemental capabilities as yet unmatched in machines. The ability to deal with the unexpected and unanticipated is the strongest attribute of the EVA astronaut, and one which needs to be preserved in the space telerobot through transparent operator interfacing.

Several general performance goals result from the desire to provide EVA equivalence in a system suitable for space application. These are summarized below:

1. Force-reflecting replica master teleoperated control for demanding operations,

2. Sensory-driven robotic operations for anticipated events,

3. Redundant kinematics for local obstacle avoidance,

4. Dual arm system,

5. High bandwidth communications link with local intelligence,

6. Position or force control,

7. Graphic menu interface for operator interaction, and

8. Reliable and modular for rapid repair or reconfiguration.

Two fields of related technology are available to establish benchmarks for technical feasibility: Teleoperator systems have been used for many years to allow humans to remotely manipulate hazardous materials, and industrial robotics have recently experienced rapid expansion resulting from advances in control technology. These two technologies utilize different design approaches optimized for their respective modes of operation. Table 1 summarizes the key elements of these manipulation technologies and provides detailed performance goals for the space telerobot.

PAST REMOTE MANIPULATION EXPERIENCE

Over the past several years, the U.S. Department of Energy Consolidated Fuel Reprocessing Program has sponsored a world-leading teleoperation development program. Initially, a TeleOperator Systems SM-229 teleoperator was employed in the Remote System Development Facility (RSDF) for human factors experiments and special remote equipment developments.[2] A second system using the M-2 teleoperator from the Central Research Laboratories of Sargent Industries was integrated into the Remote Operation and Maintenance Demonstration (ROMD) facility.[3] This system was used successfully to remotely operate a Fairchild satellite refueling coupling (see Fig. 1). Total task time was about 35 min with minimal practice training, compared with about 15 min for suited astronaut water-tank simulations. Teleoperation task time would be greatly reduced if the coupling was redesigned for remote operation. A third system, the recently developed Advanced Servomanipulator (ASM) system, designed to improve reliability and maintainability through gear drives and modular construction, is operating in the Advanced Integrated Maintenance (AIMS) Facility.[4]

These efforts have produced extensive information and experience of great value in developing new telerobotic systems. Some of the capabilities that have been developed include control techniques such as special compensation algorithms, and adaptive gain, as well as prediction of force-reflection thresholds and backdrivability characteristics. Equally important are the effects of different kinematics and different configurations on work task efficiency and obstacle avoidance. The space telerobot applies this experience to the general problems of space teleoperations.

Table 1. Space Telerobot Criteria Development

Good force-reflecting teleoperator	Good industrial robot
End effector speed 1 m/s	End effector speed 1 to 2 m/s
Friction 1 to 5% of capacity (at expense of increased backlash)	Friction 30 to 100% of capacity
Medium to low backlash	No backlash (at expense of increased friction)
Replica master control	Teach pendant, keyboard
25 to 50 mm deflection at full load	Minimal deflection at full load (0.25 to 1 mm)
6 DOF and end effector	4 to 6 DOF and end effector
Bilateral position-position control for force reflection with man in the loop	Force feedback with 6-axis end effector sensing
Relatively low inertia for minimum fatigue	High inertia for stiffness
Kinematics approximately manlike	Kinematics mission dependent
Accuracy and repeatability not important	Accuracy and repeatability very important
1:4 to 1:10 capacity/weight ratio	1:10 to 1:40 capacity/weight ratio
Universal end effector	Interchangeable end effectors

TELEROBOT

End effector speed 1 m/s
Friction close to teleoperator, much lower than robot
Backlash close to robot, much lower than teleoperator

Replica master control preferable, joysticks and autonomy research possible
0.5 mm deflection at full load
7 DOF and end effector

Bilateral position-position control for force reflection
Low inertia compared to robots
Manlike kinematics for dexterity in teleoperation

1:4 capacity/weight ratio
Universal interface for NASA end-effector research
Capacity of 9 kg continuous, 14 kg peak

Arm cross section to reach inside 150 mm x 150 mm opening

THE TRACTION-DRIVE REDUNDANT KINEMATIC TELEROBOT

The kinematics ultimately determine the dexterity of the manipulator and dictate its mechanical complexity. Most available industrial robotic systems are composed of six or fewer degrees of freedom for position and orientation of the end effector. Complete position and orientation within the reach of a manipulator requires at least six degrees of freedom, three for positioning (usually associated with the shoulder and elbow), and three for orientation (usually associated with the wrist). The major goals for the kinematics of this new telerobot were EVA-equivalent operation, elimination of midrange singularities, and large volumetric coverage. To approach EVA-equivalent operation, the kinematics should be about 100 to 150% human size and provide local obstacle avoidance. This second feature is most easily accomplished by adding a redundant joint. More detailed justifications for the redundant kinematics are given by Hollerbach.[5] The additional degree of freedom should be grouped with the positional joints to provide positional obstacle avoidance similar to the capabilities of the human arm. It should also be accomplished by simple mechanical methods. Achieving kinematic goals with a highly complex mechanical system would not be a successful solution. A more appealing solution would be simple enough to allow repeating the mechanism at each joint. This would allow using modular subassemblies, significantly reducing design and fabrication cost.

The results of these goals are a seven degrees-of-freedom arm mechanism that provides kinematic redundancy for obstacle avoidance. The telerobot is shown in Fig. 2 performing a satellite refueling operation (as demonstrated with the M-2) from the shuttle. This arm is constructed of three identical pitch/yaw joints which combine to provide shoulder, elbow, and wrist joints. An output roll at the wrist completes the system. This arrangements results in a kinematic structure whose inverse kinematics are easily found for path planning, provided that assumptions on the elbow location are made.[5] The pitch/yaw joints are derived from the technology that was developed in the ORNL Advanced Servomanipulator (ASM) wrist (Fig. 3). The ASM wrist uses a triple-nested differential that provides three orthogonal, intersecting rotary axes. A simple manipulator element which results from using only the pitch and yaw motions is the basis for the replicated subassembly.

Comparison of the resulting volumetric coverage (see Fig. 4) shows that this arrangement offers extended reach over typical six degrees-of-freedom manipulators. The implementation limits singularities to the extremities of the motion range. In this position, the joints are operated at right angles to each other, a very unusual and awkward stance, therefore these singularities do not limit operations.

The telerobot can be reconfigured to approach the worksite from a number of different directions. Four standard working orientations are shown: anthropomorphic, over the wall, sidewinder, and under the table (Fig. 5). With this diversity of stances (multimorphic), obstacles in any position can be avoided. Additional joints can be attached or extending segments can be used to reconfigure the arm for exceptional work site constraints. Additionally, the reorientation of the lower arm allows presentation of the wrist in optimal manners for control of forces generated by the arm on the worksite.

Each joint assembly consists of a differential drive mechanism, two servomotors with speed reducers, two torque sensors, and two encoders. The speed reduction ratio through the differential is 3.75 to 1. All items are totally enclosed in a aluminum housing, as shown in Fig. 6, with outside dimensions of 430 mm long, 100 mm wide and 100 mm high. The assembly is estimated to weigh 12 kg. The most significant advantages of this mechanical system are low backdrivability, smoothness of operation, high stiffness, simplicity, zero backlash, built-in clutch protection, and output position encoding.

The differential drive mechanism has two inputs and two outputs that rotate about orthogonal axes. Force transmission through the differential drive mechanism is accomplished by traction drives. Unlike force transfer through gear teeth which generate torsional oscillation as the load transfers between teeth, force transfer through traction is inherently smooth and steady without backlash and relatively stiff in comparison.[6] The elements of this traction differential drive can be seen in Fig 7. Two driving rollers provide input into the differential. A significant advantage in this setup is that each driven roller is required to transmit only one-half of the total torque necessary to make a particular motion. These rollers interface with two intermediate rollers which in turn drive the pitch/yaw roller about the pitch and yaw axes. The axis about which the pitch/yaw roller rotates depends upon the direction of rotation of the driving rollers. The pitch/yaw roller is driven about the pitch axis when the driving rollers rotate in opposite direction. When both driving rollers are rotated in the same direction, the pitch/yaw roller is driven about the yaw axis. The driving rollers and pitch/yaw roller are equipped with a belleville spring preload mechanism to ensure proper traction. The belleville spring preload mechanisms apply thrust loads on the driving rollers and pitch/yaw roller. This thrust load produces the normal load between the rollers necessary to provide adequate traction to transmit the required torque.

The rolling surfaces will be lubricated with traction fluids developed by NASA Lewis Research Center. These lubrication media will vary for space applications from those used in ground-base applications.[7]

The location of motors and the transmission of torque is a design consideration that ultimately affects system performance. The first design choice is between localized and centralized positioning of actuators. Centralized actuation minimizes the mass and inertia of the moving arm members, but it requires many linkages to transmit torque from the motor to the joint output. Centralized actuation has been used on most teleoperator systems for earth operations (Central Research Laboratories Model M-2, TeleOperator Systems SM-229, Oak Ridge National Laboratory ASM) to minimize inertia and reflected loads in these force-reflecting systems. In the microgravity environment of space, the mass of joint members does not place a continuous load on the preceding joints. Localized actuation reduces torque transmission elements and permits electrical rather than mechanical modularity at the expense of some increase in system inertia. Many robotic systems are constructed in this manner (the PUMA is the most recognized). For modularity and simplicity in a microgravity environment, localized actuators were selected.

Speed reduction and transmission of torque from motor to joint output affects the linearity of position and torque control as well as the reliability of the manipulator. The design choices for speed reduction/torque increase include direct-drive motors, planetary gearing, harmonic drives, and traction drives. Direct-drive motors do not provide a geometrically satisfactory alternative due to the large size necessary for the torque ranges required. Planetary gearing is compact, but suffers from backlash whose effects are difficult to control in a microgravity environment. Harmonic drives eliminate the backlash problem, but they inject a nonlinear torque ripple into the drive train as a result of their method of speed reduction. Traction drive reducers provide backlash-free and torque ripple-free speed reduction, and have been developed for space applications.

A commercially available planetary gear reducer has been selected to provide a speed reduction of 30:1, which permits backdrivability with a low force-reflection threshold. In future iterations, this reducer would be specially designed to meet the necessary requirements for space application. The performance characteristics, such as speed and load limits, can be varied simply by changing the reduction ratio of this reducer. Brush-type dc servo motors power the differential mechanism as shown in Fig. 6. These motors drive through speed reducers and torque sensors. The motors used are Inertial Motors Corporation Model M17B. Torque sensors used are GSE Corp. rotating torque transducers (Model 2025). Renco, Inc., optical encoders (Model R-60) are used for position information. Future developments could incorporate a precise Inductosyn for position encoding, but one is not readily available in the size necessary. These sensors provide the control system signals indicating the payload weight and location. Encoders are located on the pitch and yaw axes to maximize accuracy. By locating these encoders directly at each joint axis, the possible traction slip through the differential rollers will not affect the positioning characteristics.

The joint assembly will be fabricated using common shop practices and tolerances. The traction rollers will be fabricated from high quality case- or through-hardened gear or bearing steel such as AISI 440C. The rolling surfaces will be polished to a 4-rms finish to ensure a long service life. The housing will be formed from an aluminum alloy, such as AISI 6061-T6, into a closed tubular cross section to provide minimum weight and maximum stiffness.

Cabling provisions have been made to eliminate use of external pigtails and connectors. These provisions are illustrated in Fig. 6. A through passage within the differential mechanism contains the cabling arrangement. This cabling arrangement consists of a flat cable bundle, wound in two coils and positioned about the pitch and yaw axes within the through passage. These coils accommodate rotations about both the pitch and the yaw axes. The cabling arrangement is also equipped with electrical connectors positioned at each mounting interface. These connectors engage and disengage automatically as the joints are attached and detached.

The wrist roll mechanism is illustrated in Fig. 8. This mechanism has a motion range of $\pm 180°$, a maximum velocity of 9 rad/s, and torque capacity up to 35 N•m. Its mechanical interface will accommodate many end effectors and incorporates a quick connect/disconnect attachment method similar to that on the ASM. Each end effector module will be modified or designed to be replaceable from the wrist. This capability also allows direct attachment of special tools to the wrist without using the end effector. Electrical connectors are also mounted in each interface surface. These connectors would engage and disengage automatically as the end effectors are attached and detached.

Each joint, weighing only 12 kg, has been designed to carry a 14 kg payload at a distance of 0.37 m from its orthogonal axis. The maximum no-load speed at this distance is 1.3 m/s. The arm's total reach using three identical joints of minimum length (400 mm) is 1.1 m when measuring from the shoulder pitch axis to the center of tong's grip. In this outreached position, the arm will comply under a 14 kg payload with a maximum deflection of 0.5 m while maintaining a total positional accuracy of ± 1.0 mm.

Computer-Aided Three-Dimensional Interactive Applications (CATIA) is a three-dimensional modeling package developed by Dassault Systems (France) and marketed by IBM. It was used to develop a kinematic model of the telerobot. Figures 9 and 10 are CATIA plots of the model. Some of the CATIA modules used to develop these plots are kinematics, robotics, and solids.

The arm will be counterbalanced to simulate 0-g by using a single mass of approximately 20 kg. The mass is attached mechanically to the arm through an innovative arrangement of a four-bar linkage that counterbalances both shoulder and elbow joints. This arrangement has been chosen to minimize the additional inertia. The wrist will be electrically counterbalanced to further reduce the system's total inertia.

CONCLUSIONS

A concept for a space telerobot was developed for NASA Langley Research Center. This concept incorporates modular, replicated manipulator elements to provide redundant kinematics in a package approximately the size of a suited human. This telerobot will employ traction drive technology to eliminate backlash and reduce torque nonlinearities associated with available speed reduction mechanisms. The arm will be capable of teleoperated or robotic operation for maximum operational flexibility and reduced manpower.

Construction and maintenance of a space station is a significant challenge. The technology to augment human activities in this environment is available but not properly configured for the tasks at hand. Efforts toward development of an EVA-equivalent manipulator will return benefits for generations to come, both in space and on earth. A successful space manipulation system will expand the productivity and capabilities of man in this remote, challenging environment.

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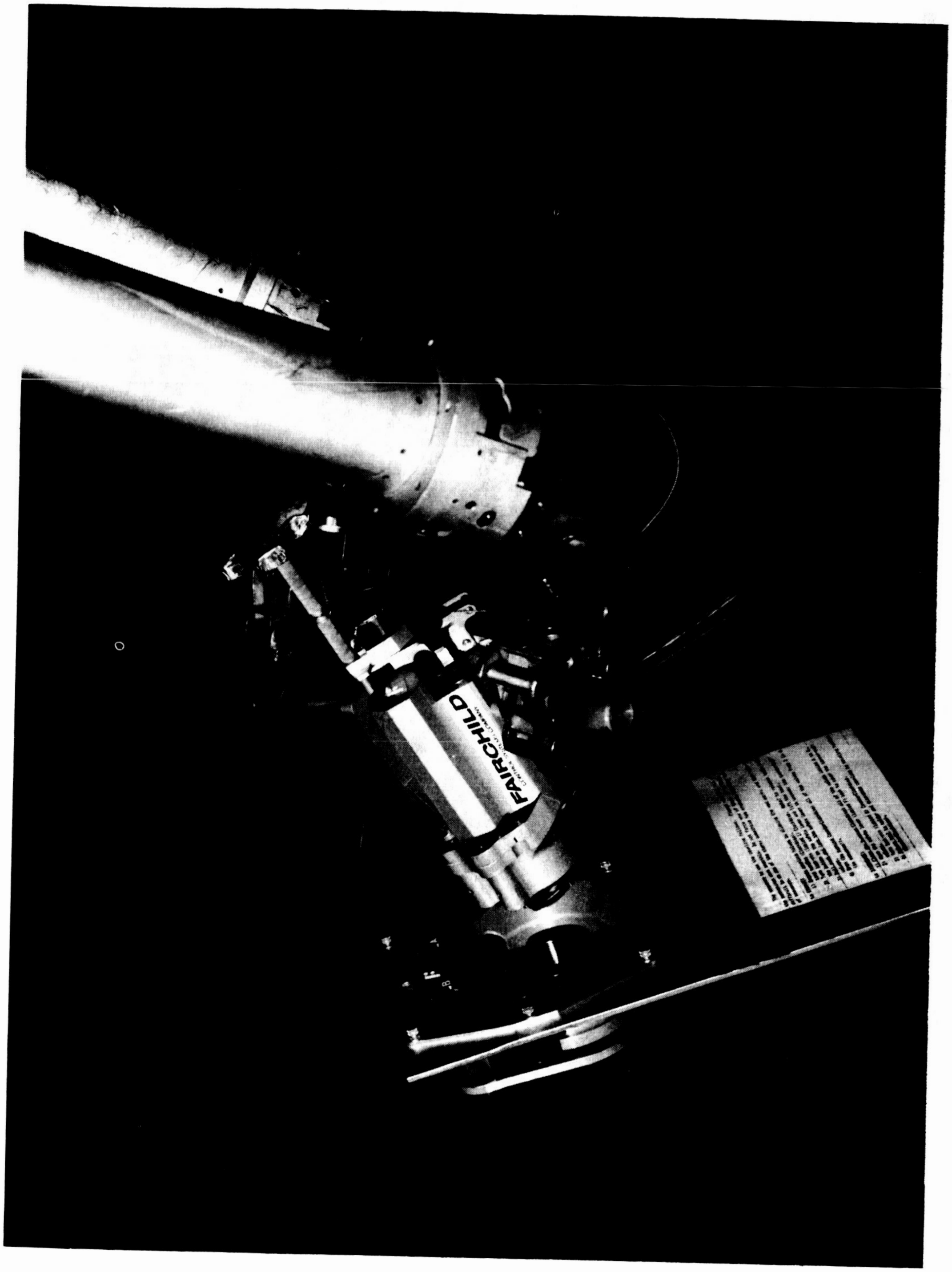

Fig. 1. M-2 operating Fairchild satellite refueling coupling

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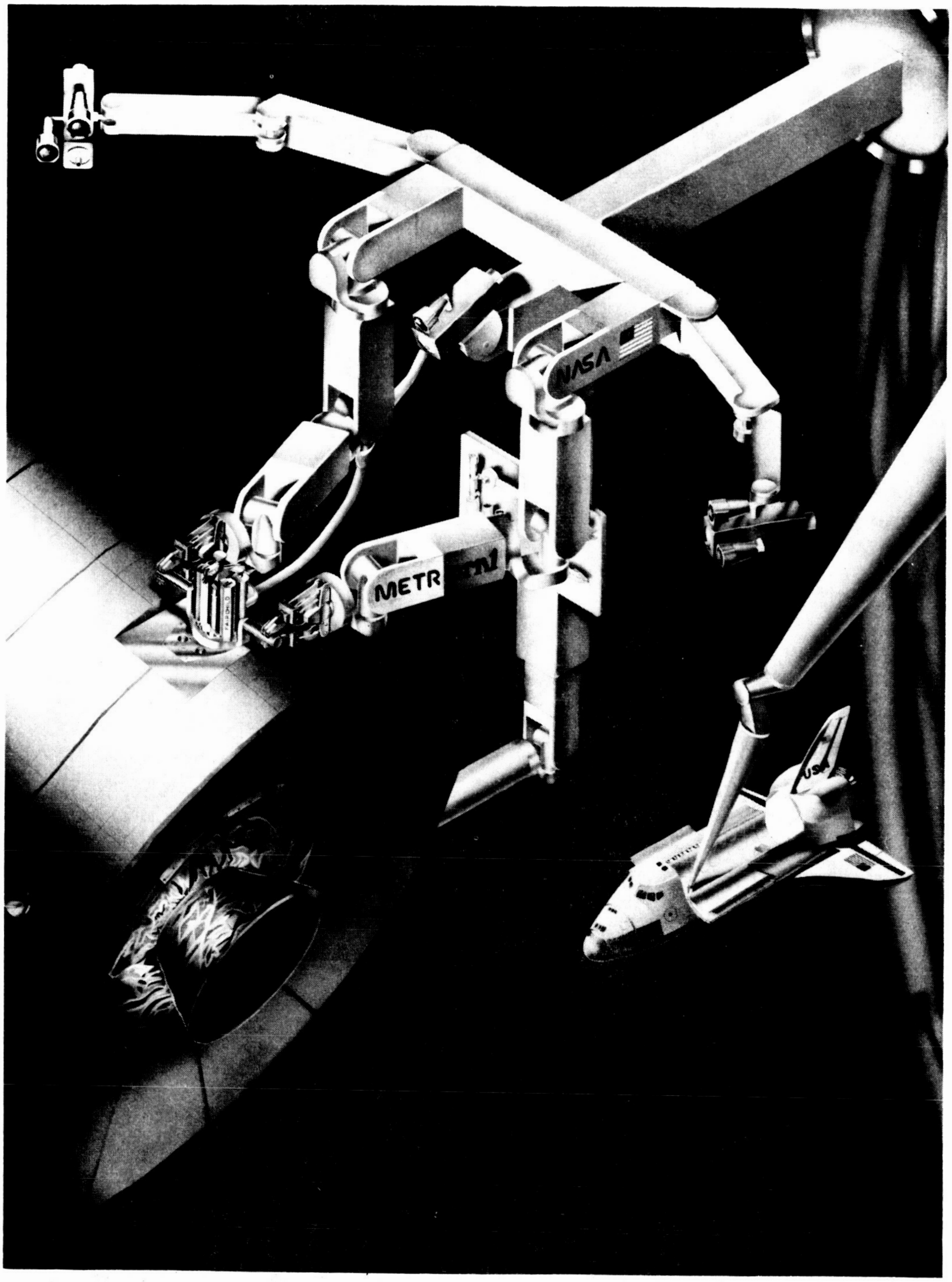

Fig. 2. Telerobot refueling satellite

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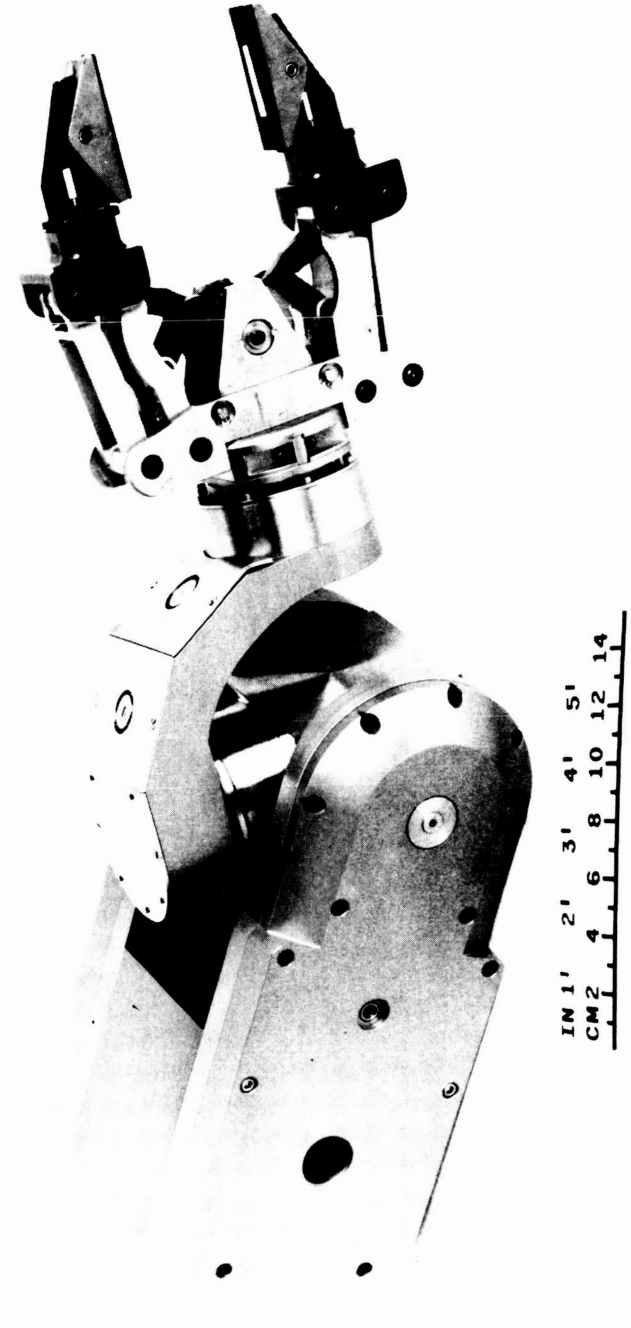

Fig. 3. ASM four degrees-of-freedom wrist

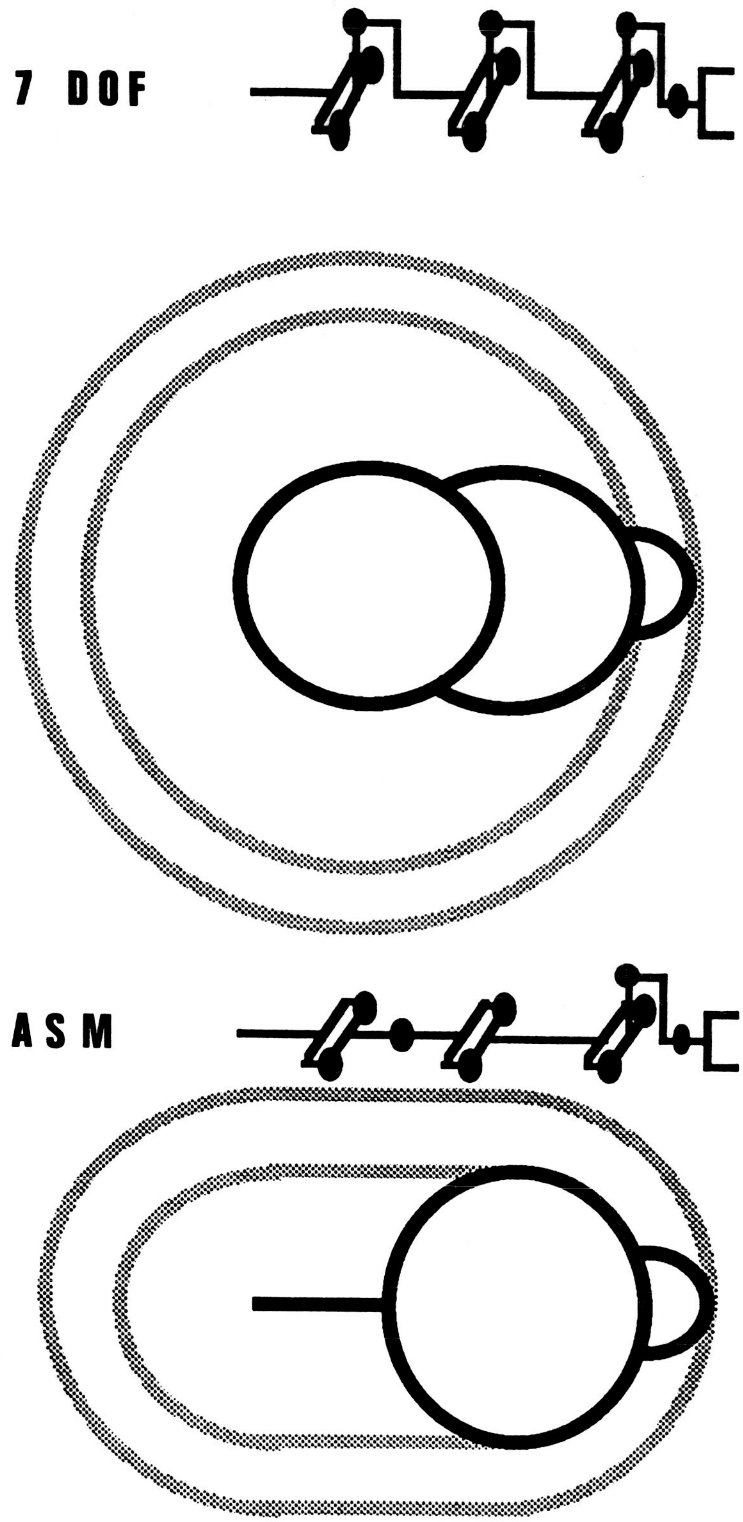

Fig. 4. Comparison of volumetric coverage: 7 DOF telerobot and ASM

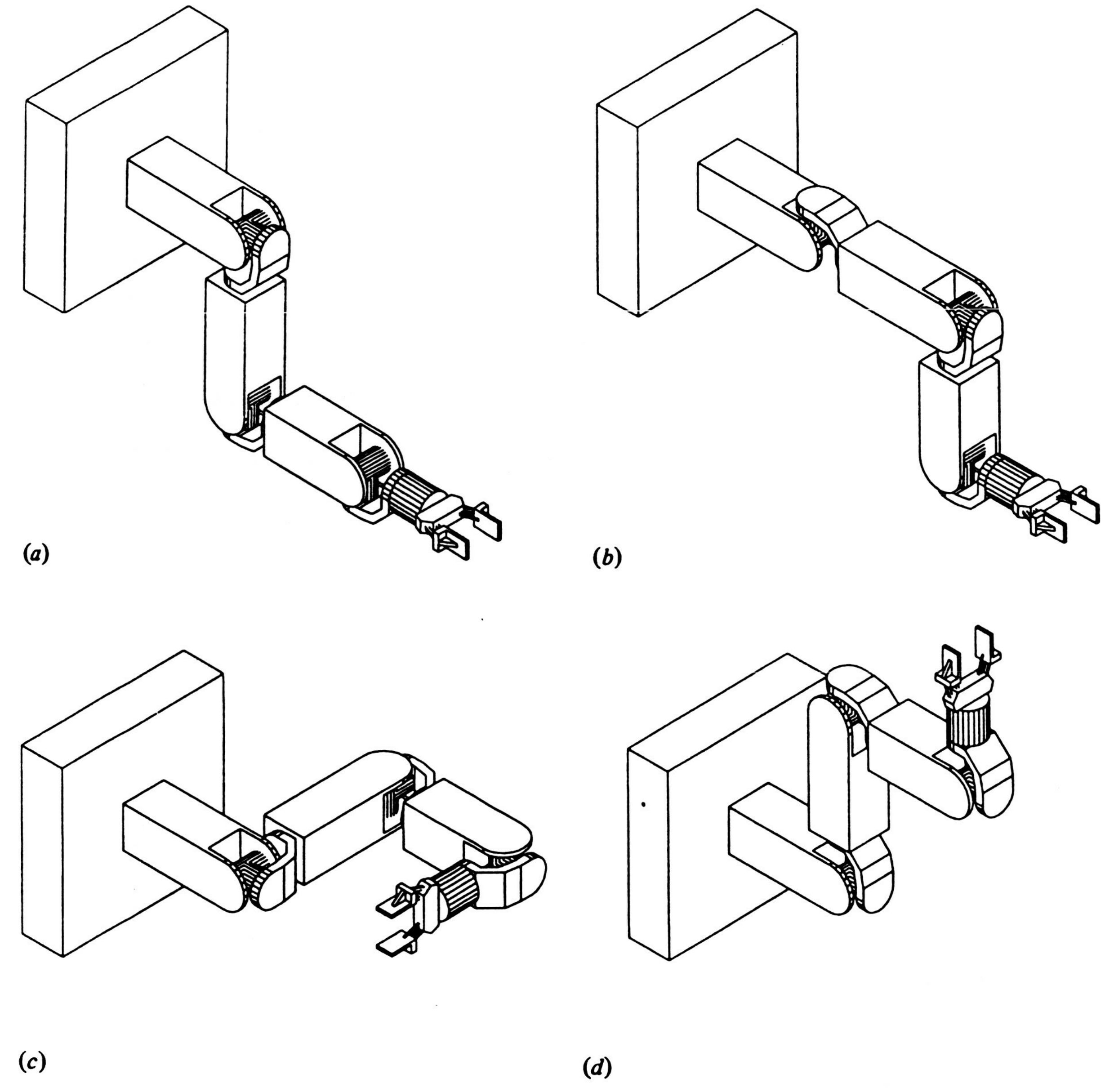

Fig. 5. Examples of kinematic dexterity and active reconfigurability: (a) anthropomorphic, (b) over the wall, (c) sidewinder, and (d) under the table

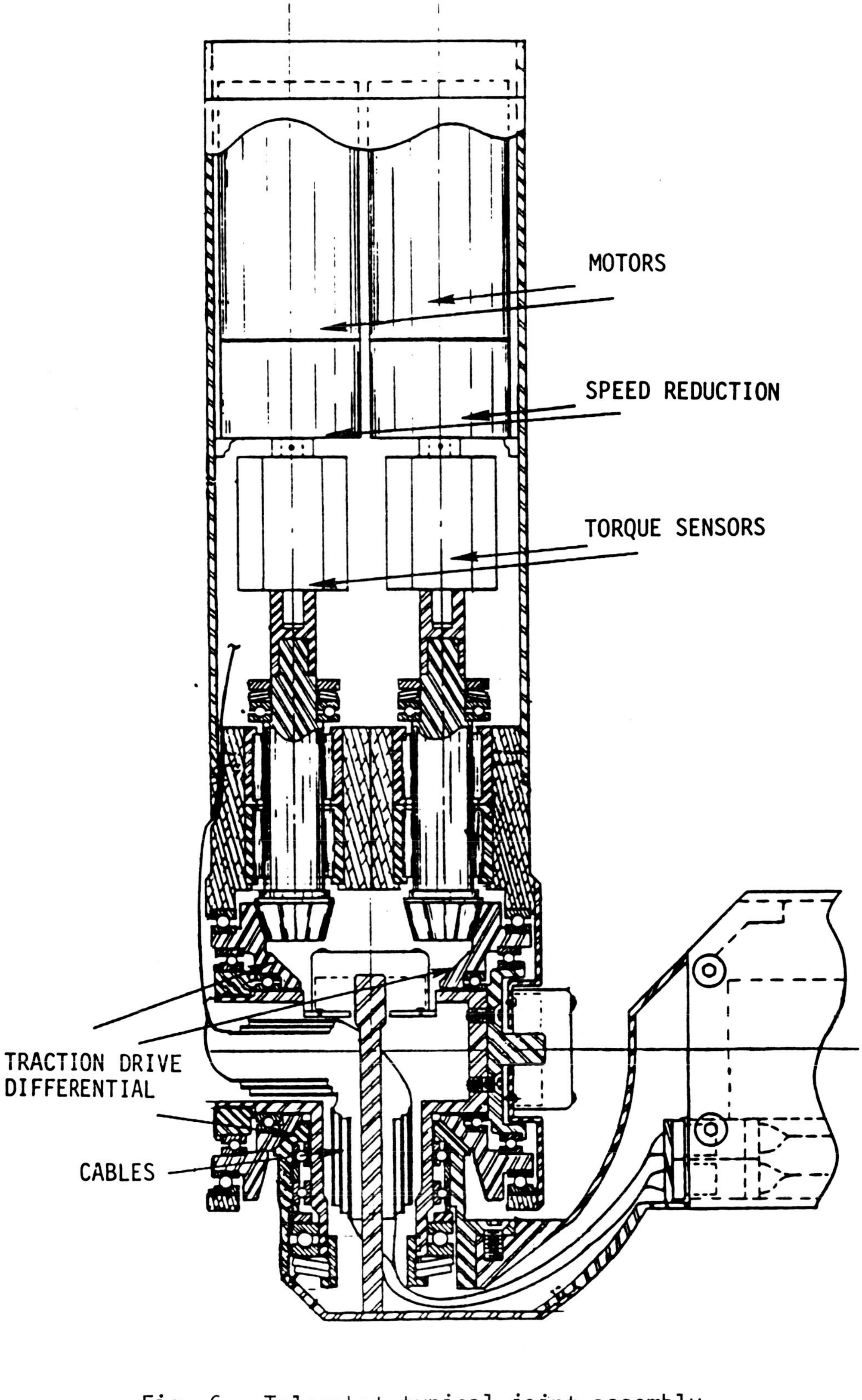

Fig. 6. Telerobot typical joint assembly

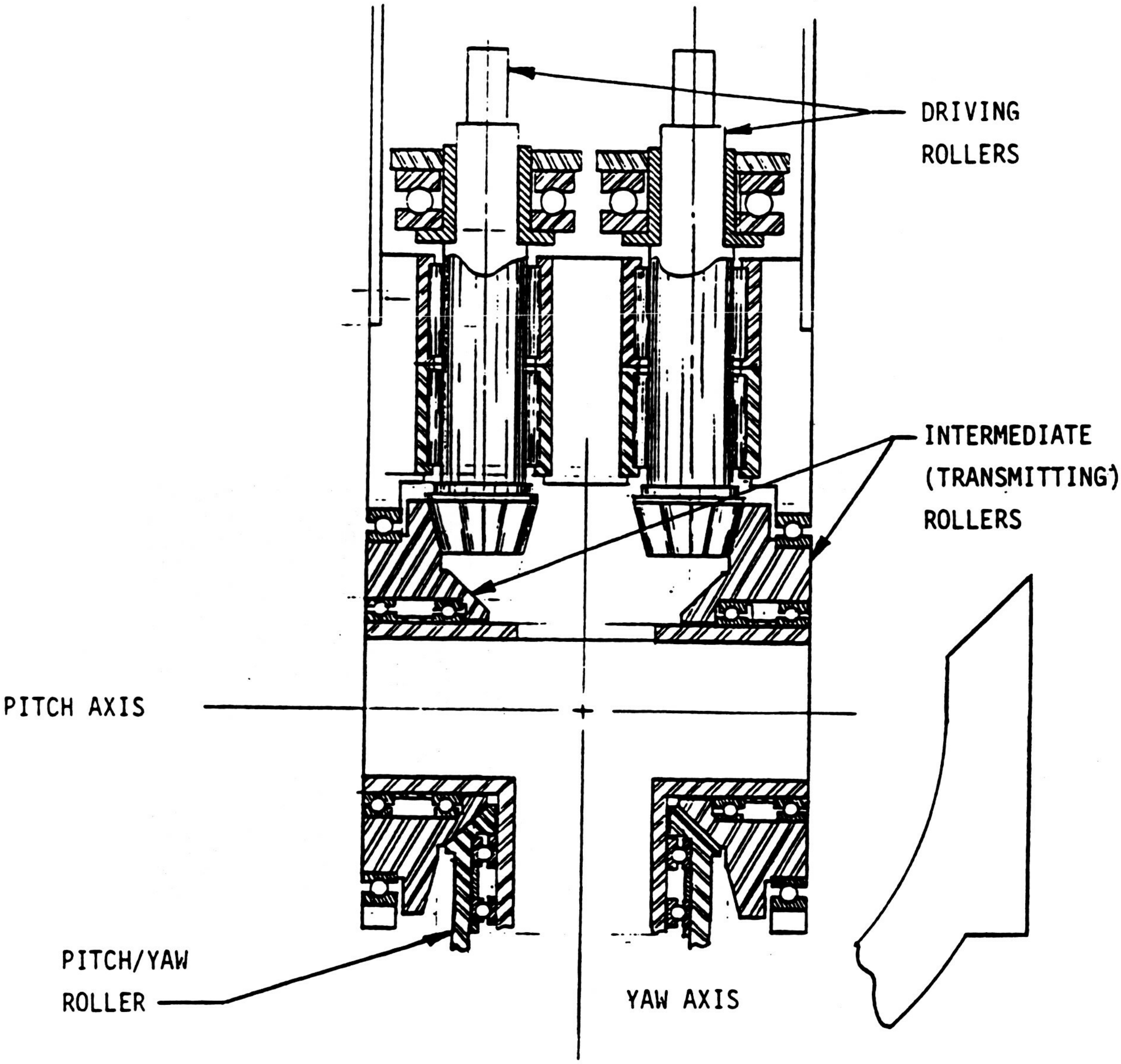

Fig. 7. Traction drive differential

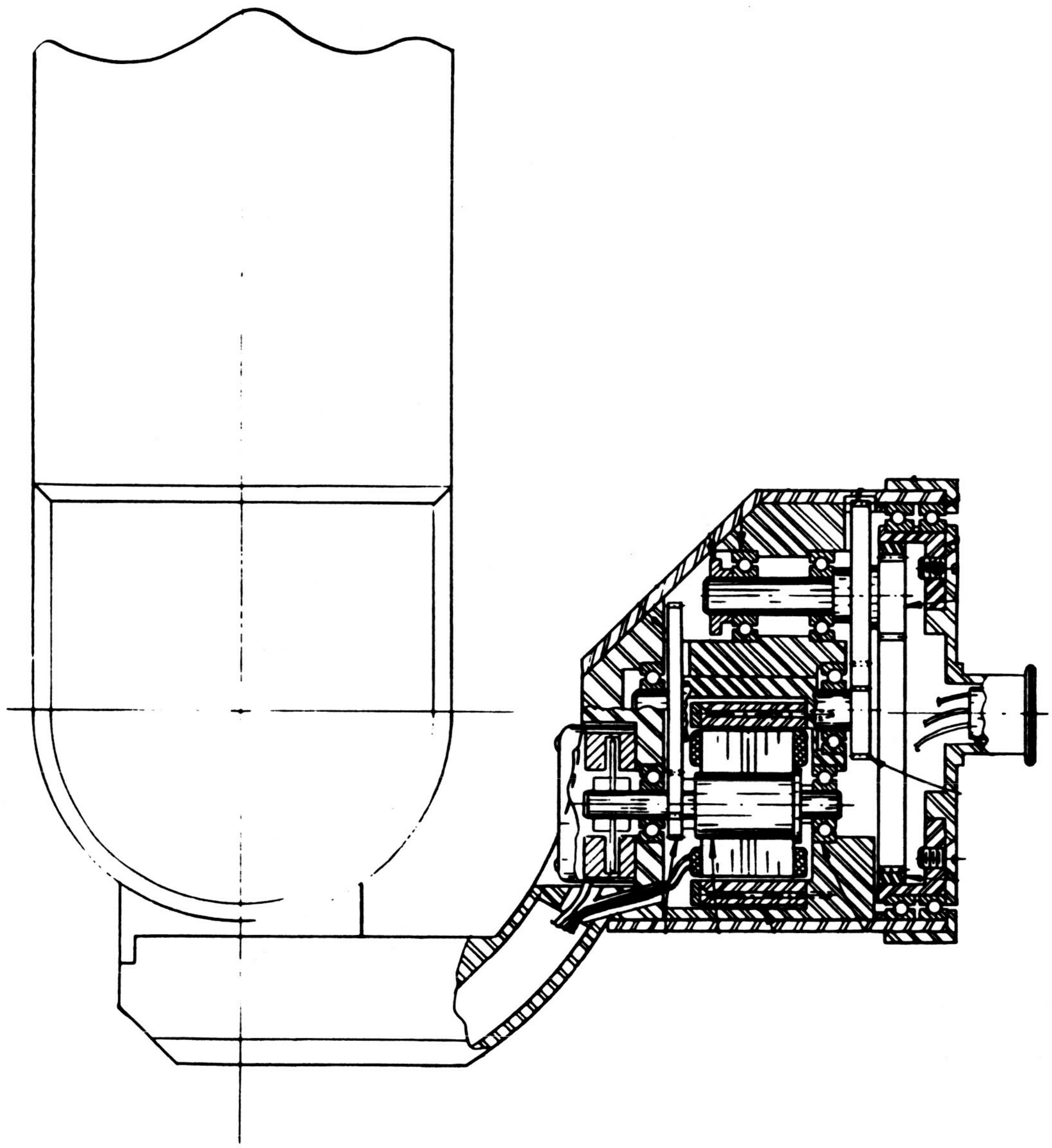

Fig. 8. Telerobot distributed wrist roll joint

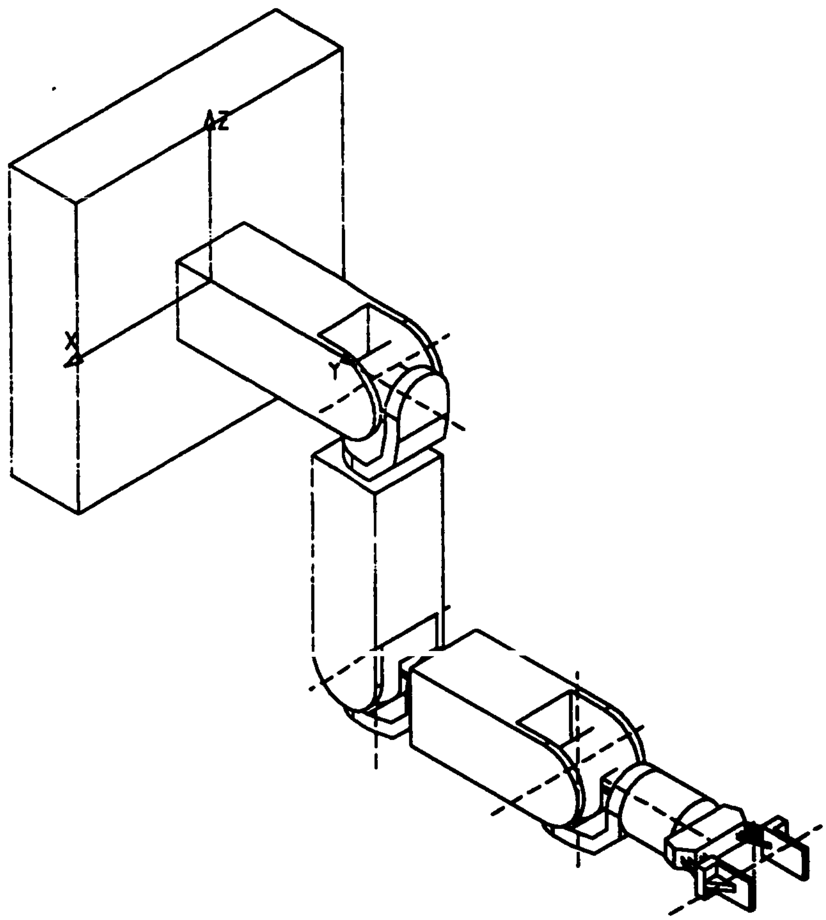

Fig. 9. Telerobot kinematic model

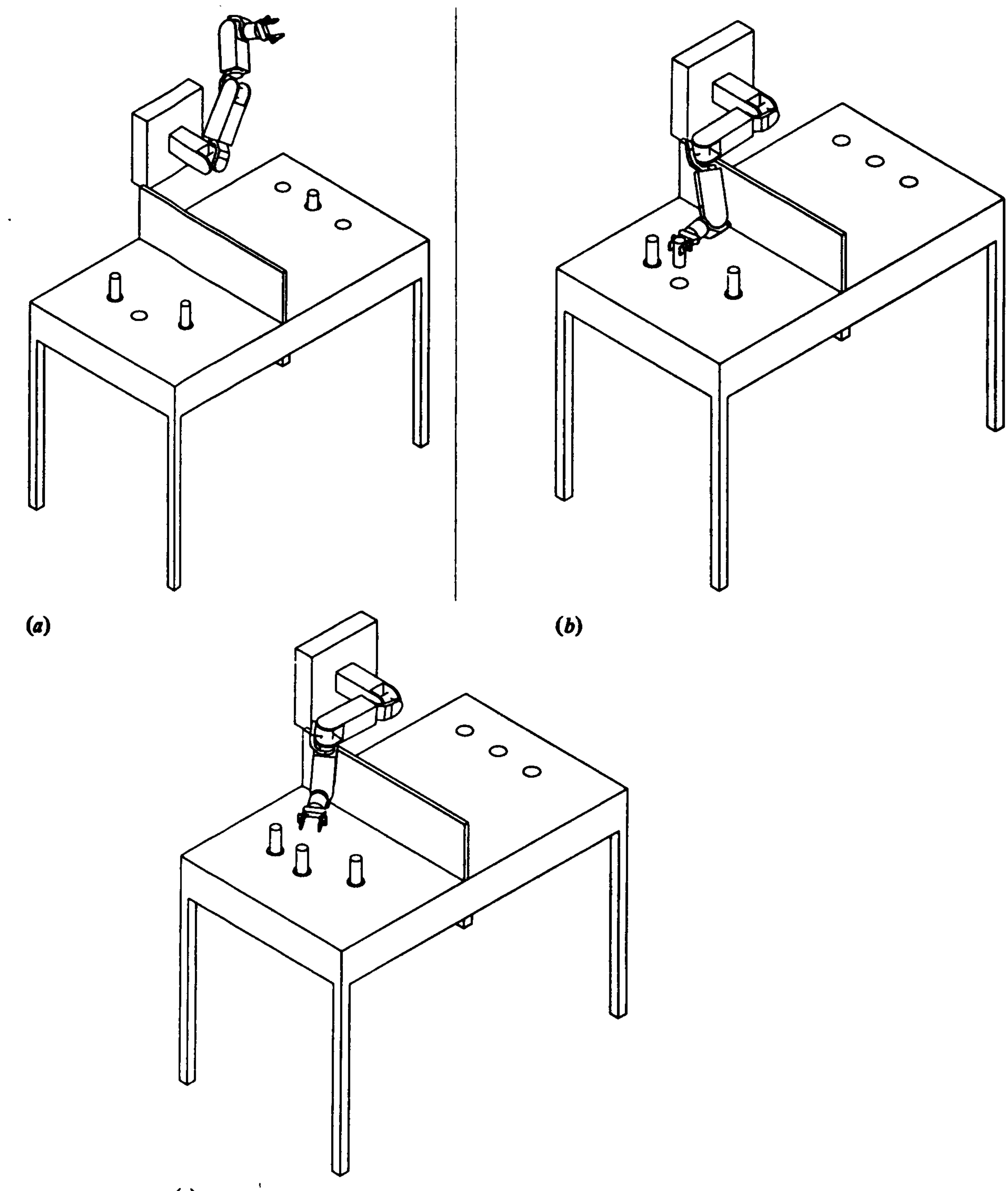

Fig. 10. CATIA simulation of telerobot performing task around an obstacle: (a) step 1, (b) step 2, and (c) step 3